Enhancement of Learning in Aircraft Handling Qualities Through Variable Stability Flight Simulation

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Abstract: There is an inherent need for aerospace engineering students to understand the meaning and consequences of flight stability and response to pilot control inputs. For most, limited flying experience makes learning this connection difficult. A full-motion flight simulator has been specifically developed to demonstrate a range of aircraft flight responses. Experiential learning exercises give first-hand experience of various important aerodynamic parameters used in aircraft design, and the effects that they have on an aircraft handling qualities. This paper discusses the facility, the background to the problem, and the form of the experiments performed. It presents the methods of analysis used to assess the effectiveness of the experiments and the facility. Learning outcomes from before and after knowledge analysis show a substantial improvement. Student feedback also shows great enthusiasm for this teaching system and indicates that students draw great learning benefits through experiential learning and their exposure to motion-based flight responses.

Introduction

The School of Aerospace, Mechanical and Mechatronic Engineering (SAMME) at the University of Sydney has been developing its Variable Stability Flight Simulator (VSFS) since 1999. The simulator has been integrated into the School's undergraduate coursework syllabus since 2006 as an instrument for providing experiential learning in flight mechanics. This paper presents teaching and learning achievements from these first three years of operation. Development of this facility commenced in 1999 and involved complete re-engineering of a decommissioned Link 707 simulator acquired from the RAAF, with the view to providing a generic flight simulator to enhance engineering training in aircraft flight stability, handling and control concepts. This process took six years of design and system integration. The simulator has full three-degree-of-freedom motion and has been designed to provide the operator with full control over the aircraft's aerodynamics and flight characteristics. The aircraft's dynamics can be altered in real-time so that particular concepts can be immediately felt and compared in the consequent dynamic behaviours. This capability is a world first, though Sheffield University (a collaborator) in the UK have developed a similar capability although without the critical element of motion. Motion feedback is important to give the vestibular feedback required to make the flight dynamic responses feel realistic, thus allowing students to distinguish subtle differences in dynamic responses. The University of Sydney is the only Australian university with such a facility. Further project information can be found on the project web site (Gibbens, 2009).

As long as Flight Mechanics has been taught in SAMME, it has been well known that students have difficulty grasping concepts of flight dynamics and control through traditional teaching methods alone. This is due mainly to the fact that most students have little or no flying experience with which to connect practical handling responses with the theory. Even established pilots usually only have experience on a few similar aircraft types. Novice students are given 4-5 hours of basic flying experience which exposes them to the basic operation of an aircraft and its controls, and the issues (like pilot workload and turbulence) that influence good design for handling qualities in order to provide some background. However, the importance of variations in flight dynamics properties for a range of aircraft types from general aviation through commercial and military aircraft cannot be feasibly demonstrated in a university environment because of cost and accessibility constraints. This is a luxury enjoyed only by dedicated flight test engineering academies (e.g. NTPS 2009, Calspan 2005). In aeronautical design, however, it is crucial that students have a good working knowledge of handling qualities in a broad range of aircraft types. This motivates flight simulation as a cost effective and efficient means of providing first-hand experience that is not realistically achievable any other way.

Experiential Learning

The third year unit of study AERO3560 Flight Mechanics 1 develops the principles of aircraft stability, controllability and handling qualities. Students study key aerodynamic properties and their effects on these flight characteristics. Without extensive flight experience, it is difficult for them to appreciate how these handling qualities change with aerodynamic variations and what characteristics represent *good* handling qualities.

It is to address this deficiency in the engineering education programme that the flight simulation initiatives were introduced (Rickard and Gibbens, 2006). Experiential learning exercises have been designed that demonstrate the effects of key aerodynamic properties on the stability of the aircraft and the way it responds to pilot control inputs. These exercises commence by allowing students to fly a reasonably responsive aircraft in a nominal condition. Aerodynamic properties are then altered in real-time so that the effects of the consequent degradation in stability can be immediately observed and appreciated. The motion effects demonstrated amount to variations in the aeronautical equivalent of the common characteristics of natural frequency and damping factor observed in typical mechanical systems like spring-mass-damper systems in vehicle suspensions. However in aircraft flight there are numerous dynamic modes of motion that affect the complete handling and *feel* of the aircraft as it is free to move with 6 degrees of freedom rather than one.

Specifically the exercises study the longitudinal behaviour of the aircraft's short-period mode, a combination of vertical translation and pitch rotation that dominates the aircraft dynamic behaviour and equilibrium. It is of critical importance in the routine operation of the aircraft. They also study the lateral-directional behaviour of the dutch roll mode, a combination of rolling and yawing rotations. These are both second order dynamic motions that display stiffness and damping characteristics. It is these characteristics that determine whether the handling qualities are acceptable.

Exercises

The majority of the exercise is performed using a Pilatus PC-9 model and cover a range of scenarios as listed in Table 1. Scenarios 1 and 2 serve to familiarise the student with the nominal stability and controllability of the aircraft. Students take this opportunity to get a "feel" for how the aircraft responds to control stick movements. This involves manipulating the elevator, aileron and rudder controls to get an idea of how the nominal aircraft responds, and how to correct the aircrafts flight path and attitude. Scenarios 3 to 10 involve the aircraft initially flying straight and level. A computer generated elevator impulse is added to activate short period motion. It is the student's responsibility to then bring the aircraft back to **straight and level flight** as quickly and smoothly as possible.

Students are guided to take note of the following

- How easy or hard the aircraft was to control?
- How well the aircraft responded to the control inputs?
- Did the aircraft need multiple corrections in pitch attitude to keep it flying level?

Scenarios 11 to 19 involve the aircraft initially flying straight and level. A computer generated rudder impulse is then added. It is the student's responsibility to then bring the aircraft back to **straight and level flight** on the initial heading as quickly and smoothly as possible. Students are guided to make similar observations including whether multiple corrections in bank angle are needed to keep it flying on the designated heading. Scenarios 16 and 17 involve flying a Boeing 747 and a fast military jet respectively in clean configuration in order to demonstrate radically different response rates.

No	Configuration	Control Impulse	Turb-ulence	Purpose
1	Nominal (no motion)	-	Off	To get a basic feel of the aircraft response in all axes
2	Nominal	-	Off	To refine feel of aircraft response with motion feedback
3	Nominal	3° Elevator	Off	To observe the natural Short Period Mode response
4	Nominal	3° Elevator	On	To observe how turbulence necessitates increased attention to pitch and altitude management
5	Reduced pitch stiffness	3° Elevator	Off	To observe the reduction in pitch response speed and additional difficulty in control of the flight path
6	Reduced pitch stiffness	-	On	To observe the increased pitch sensitivity to disturbances
7	Reduced pitch damping	3° Elevator	Off	To observe the increase in pitch oscillation and additional difficulty in controlling the flight path
8	Reduced pitch damping	-	On	To observe the increased pitch sensitivity to disturbances
9	Reduced pitch stiffness and damping	3° Elevator	Off	To observe the overshoot in response to control and tendency towards pilot induced oscillations
10	Reduced pitch stiffness and damping	-	On	To observe pitch sensitivity to disturbances, extent of variations in flight path and inadequacy of control response in ameliorating disturbances.
11	Nominal	5° Rudder	Off	To observe natural Dutch Roll Mode response
12	Nominal	-	On	To observe how turbulence necessitates increased attention to sideslip and heading management
13	Reduced yaw stiffness	5° Rudder	Off	To observe reduction in yaw response speed and additional difficulty in controlling flight path (heading)
14	Reduced yaw stiffness	-	On	To observe the increased yaw and heading sensitivity to disturbances
15	Reduced yaw damping	5° Rudder	Off	To observe the increase in yaw oscillation and difficulty in control of the flight path (heading)
16	Reduced yaw damping	-	On	To observe the increased yaw and heading sensitivity to disturbances
17	Reduced yaw stiffness and damping	5° Rudder	Off	To observe persistence of roll/yaw oscillations, inadequacy of control, and tendency towards pilot induced oscillations.
18	Reduced yaw stiffness and damping	-	On	To observe heading sensitivity to disturbances, extent of variations in flight path and inadequacy of control response in ameliorating disturbances.
19	Nominal at higher speed	-	Off	To observe the dependence of dynamic response speed on airspeed
20	Boeing 747-400	-	Off	To observe the dramatic reduction in pitch, roll and yaw response speed, and reduced manoeuvrability
21	Jet fighter (no motion)	-	Off	To observe the dramatic increase in pitch, roll and yaw response speed, and improved manoeuvrability

Table 1: Flight simulation scenarios

Appraisal of learning effectiveness

In each year the students have been surveyed before and after the exercise to assess its direct impact on student knowledge and understanding of concepts. Questionnaires are completed that include a section of student self-assessment, a section of assessor based questions, and a section of written responses relating to the students' responses to the lab exercise and the facility. These allow a variety of assessments to be made. Firstly, the correctness of student understanding from the assessor perspective, and secondly, the effectiveness of the exercise from the student perspective. It is interesting to note that the outcomes in these two categories correlate. And finally it is a good source of information regarding student satisfaction and/or criticism, and of information relating to how the facility and exercises can be improved. Preliminary learning outcomes for the 2006 academic year were reported by Gibbens and Rickard (2007). It is important to note that the students are not directly assessed towards their course results in the lab exercise, and that the lab exercise is performed solely for the purpose of improving student learning of key concepts. Survey assessments are performed only for the purpose of analysing the effectiveness of the teaching system in terms of student learning outcomes.

- **Student self analysis** – Students are requested to rate their understanding of key concepts on a scale of 1-5 where 1: Very poor, 2: Poor, 3: Average, 4: Good, 5: Excellent. Analyses of responses shown in Figure 1 indicate that students consider they achieved significant overall improvement (~10-12%, defined by the increment relative to scale of 5, e.g. 0.6/5≡12%) in understanding from the simulation exercise. It is worthy of note that 90% of students believe that their course results will improve by 3-10% as a result of this experience. 35% of students by 5-7%. 90% of students say their knowledge has improved as a result of the lab exercise.
- **Assessor analysis** – the assessor analysis segment of the questionnaire involves 6 part multiple choice responses to a set of 20 questions that target specific knowledge concepts. Correctness is analysed before and after students undertake the laboratory session. The results are collected into categories and presented for each knowledge category. They are shown on a 0-5 scale showing how many students out of 5 (on average) give the correct response. Altogether 3 years worth of data have been analysed. These show that the learning improvements are generally consistent across the three years of operation.

Learning Outcomes

Overall learning outcomes: Preliminary results from the first implementation of the teaching systems in 2006 (Gibbens and Rickard, 2007) showed approximately 14% (i.e. 0.7/5≡14%) improvement in knowledge outcomes. Figure 1 shows data for 2007 and 2008 courses. In general these show similar levels of total knowledge uptake (10-12%).

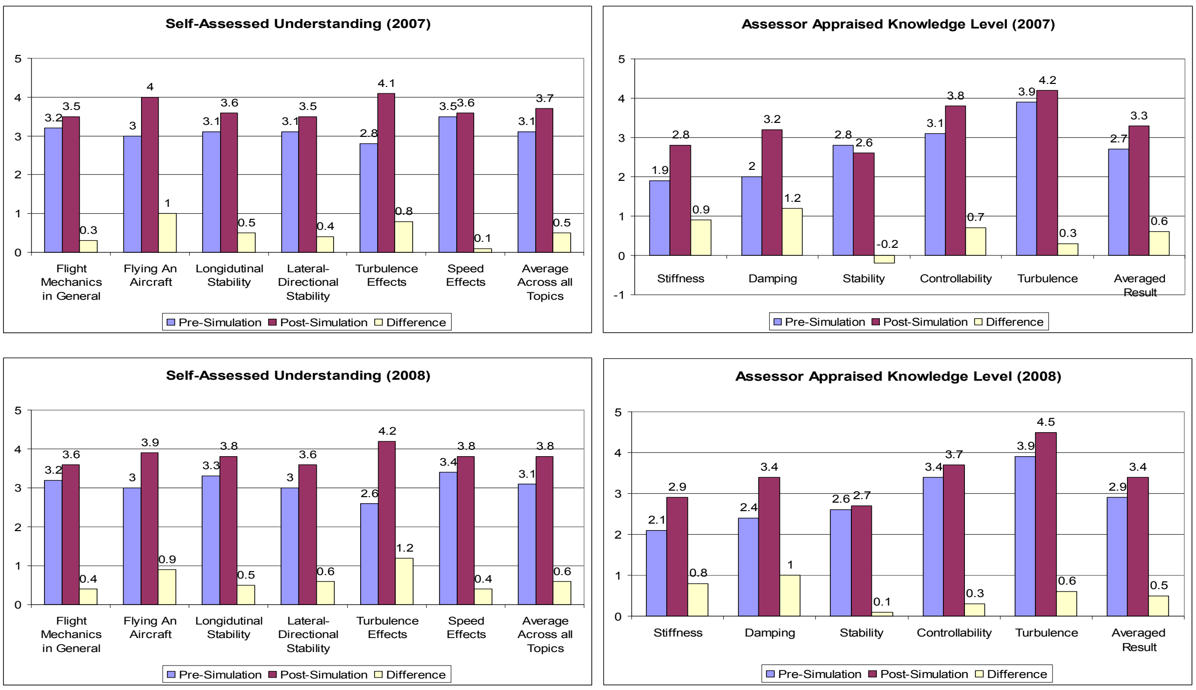

Figure 1: Average self-assessed understanding and assessor appraised knowledge (2007/8)

The student self reflection results indicate that consistent improvements are being achieved. A slight improvement of one point is observable between 2007 and 2008 student cohorts. However, from a total learning perspective it is the assessor appraised knowledge outcomes that are more meaningful. In each year the student written feedback is analysed in order to target key areas requiring improvement in teaching delivery. From this, more attention was paid in the 2008 delivery on the key concept areas of damping, stability and turbulence. In particular the 2007 class seemed to have a negative result with respect to stability, indicating that the experiential learning was misleading their understanding of this concept. With extra attention, this trend was reversed in the 2008 programme. In general student understanding on completion of the exercise was 1-3 points up on 2007 outcomes in all key areas. Although the learning increment was smaller than in 2007, this indicates that student knowledge before the exercise was higher coming into the exercise and that they had learnt better from the conventional components of the course delivery.

Demographic Advantages: Analysis of the data from questionnaires shows that significant benefits are drawn by particular demographics groups from the experiential learning sessions in the VSFS.

Effect of student flying experience – Figure 2 shows results from the questionnaires analysed against the level of student flying experience. This compares the learning achieved through the flight simulation laboratory exercises by students with little or no flying experience (<5 hours flight) to that achieved by experienced pilots. On average, the self assessment results show that inexperienced students gain an average 12% improvement in their understanding of key concepts where experienced pilots achieve far less improvement (2%). (Note that experienced pilots typically overestimate their engineering knowledge). The assessor analysis substantially supports this outcome with the significant difference that both groups make substantial gains in the main elements of aircraft stability analysis (stiffness and damping) as opposed to the more operationally significant concepts that pilots are more likely to know by experience (stability, controllability and turbulence). This is an important outcome in terms of experiential learning of engineering concepts and reinforces the initial motivation for using simulation to improve learning of these concepts for students with little flight experience.

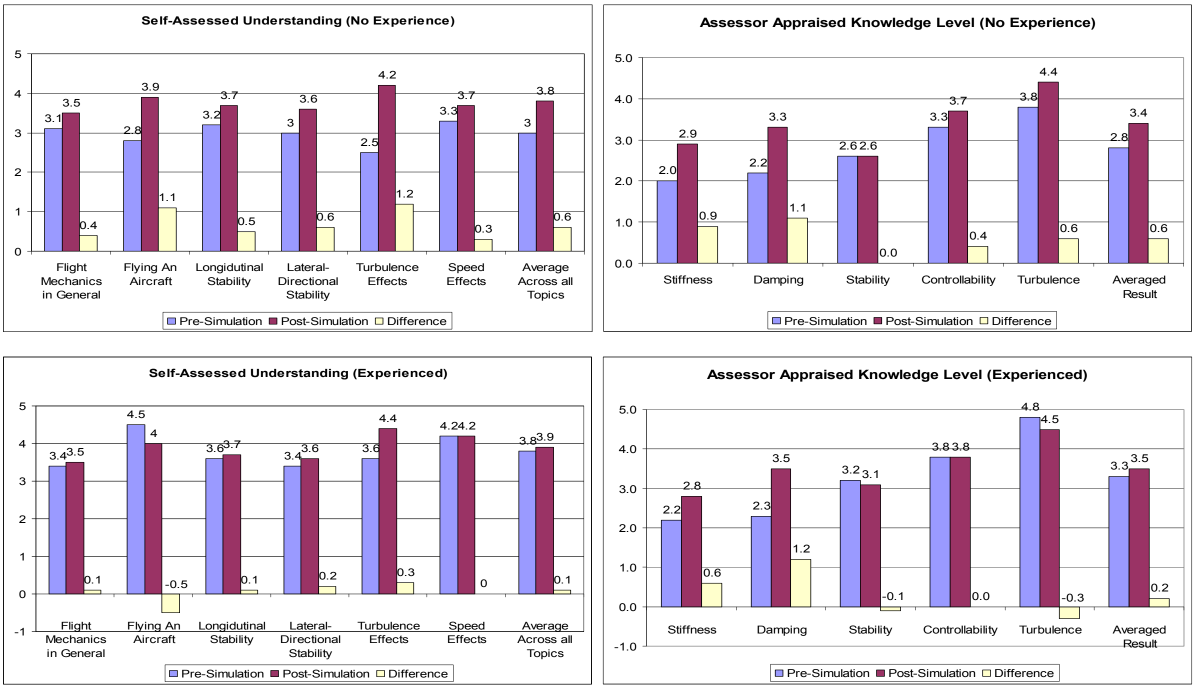

Figure 2: Self-assessed and assessor appraised understanding levels 2007/8 for students with and without piloting experience

Women in engineering – While there is no obvious reason why male and female students should learn any differently in this engineering discipline, the survey results show that female students are gaining substantially more learning benefit from experiential learning experiments than males.

In Figure 3, self analysis results show that male students are making smaller knowledge gains (~10%) than females (~16%) on average across all key concepts. Interestingly, the graphs show that females are starting at a slightly lower level, but are achieving the same understanding after the laboratory sessions. Assessor appraised results indicate about the same increments in knowledge (male ~%10, female ~%16%). Importantly though, these assessments (being based on correctness of answers) indicate that female students are in fact beginning with a better knowledge than males and achieving a greater increment to finish the experiential learning exercises with a far higher level of knowledge. It appears then that the self assessed results are a reflection of student confidence in their understanding.

Females seem to be less confident in their understanding of key concepts, but are in fact understanding them better than males. They are also benefiting more by experiential learning.

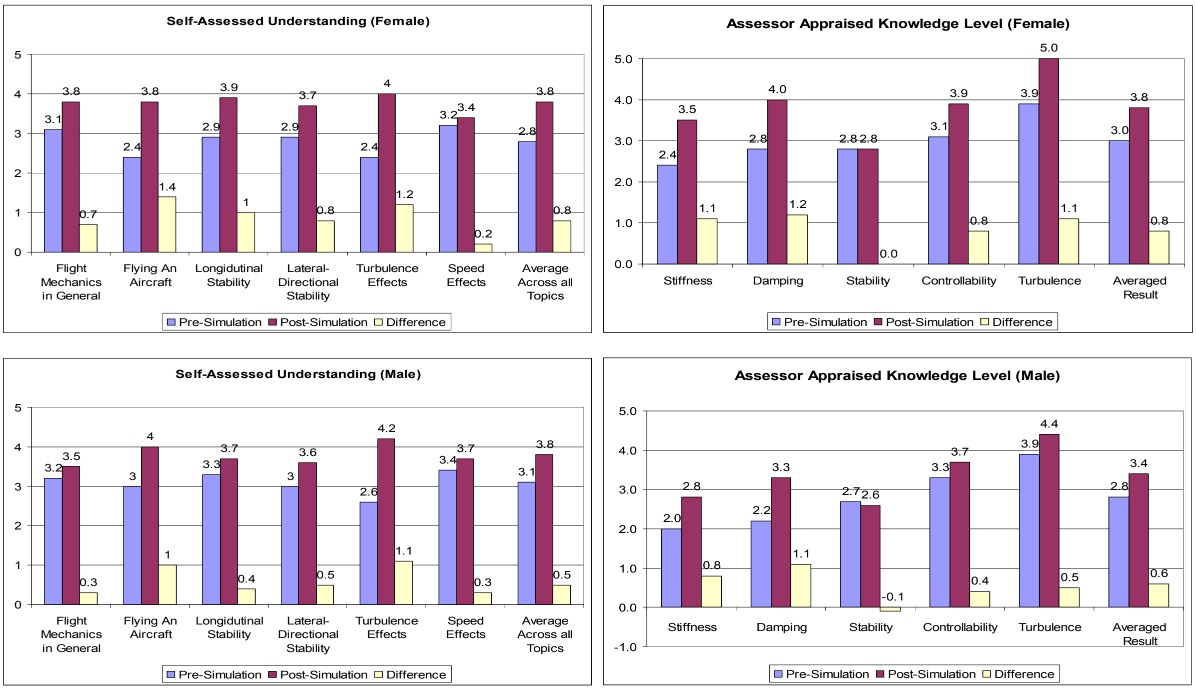

Figure 3: Self-assessed and assessor appraised understanding 2007/8 for male and female students

Conclusions

The flight simulation system and learning exercises presented herein have been specifically designed to address a pressing need for experiential learning. This is an engineering discipline that inherently suffers from a need to teach engineering students the importance of aerodynamic design in achieving good aircraft handing qualities in flight, a realm with which they little first-hand familiarity. The system has shown significant benefits over teaching using conventional methods alone. Learning improvements resulting from experiential learning have been shown to be significant and consistent, with demonstrable improvements occurring in response to targeted weaknesses. Analysis of the learning outcomes for important demographic subgroups has shown that major learning improvements are achievable for students with little flight experience relative to experienced pilots. This shows that one of the major aims of the programme has been successfully achieved. An important, though unexpected result, has been that female students are benefiting substantially more from experiential learning in a traditionally male dominated discipline. Ongoing research is investigating how further improvements can be achieved.

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